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HEAT TRANSFER IN THE LAMINAR-WAVE SECTION OF CONDENSATION OF A
STATIONARY VAPOR

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A method is proposed that specifies and refines the relation for the average coefficient of heat transfer at $Re \leq 250$.

The oscillatory motions of a phase interface resulting from the development of wave flow of a condensate film determine the intensification of heat exchange during condensation on a vertical surface [1-3].

In the existing methods of calculating the average coefficient of heat transfer in the laminar-wave section, wave formation is taken into account by the introduction of a correction factor to the Nusselt equation in the form of a constant [2] ($\overline{Nu}/\overline{Nu}_N = 1.21$) or a certain function of the Reynolds number [3]:

$$\overline{Nu} = 0.95 Re^{0.04} \overline{Nu}_N \quad (1)$$

The relation (1) has found wide popularity, despite the fact that it was confirmed experimentally only for low Reynolds numbers $Re \leq 40$ [4]. The cycle of experimental research presented in [5] revealed an excess of the experimental data at $Re > 40$ over the values found from (1), increasing with an increase in the Reynolds number. This disagreement is connected with the fact that in (1) the correction to the Nusselt equation for wave formation refers to the entire heat-exchange surface, containing both the wave section of condensate flow and the purely laminar section, in which intensification of heat exchange does not occur.

The authors propose to refine the above method of calculating the average coefficient of heat transfer (1) by the introduction of a correction factor allowing for the intensification of heat exchange only in the wave section.

Thus specifying the expression for \overline{Nu} , we obtain

$$\overline{Nu} = L^{-1} \left[\int_0^l Nu_N(x) dx + \varepsilon_w \int_l^L Nu_N(x) dx \right] = \overline{Nu}_N \left[\left(\frac{l}{L} \right)^{3/4} + \varepsilon_w \left(1 - \left(\frac{l}{L} \right)^{3/4} \right) \right], \quad (2)$$

where ε_w is the correction for wave formation, the value of which is determined by the Reynolds number, as was shown in [3].

The dependence of the coordinate of the start of development of the wave regime (l) on the parameters of the condensation process is determined from an analysis of the stability of laminar flow of the condensate film. From the results of such an investigation [6-8] for the

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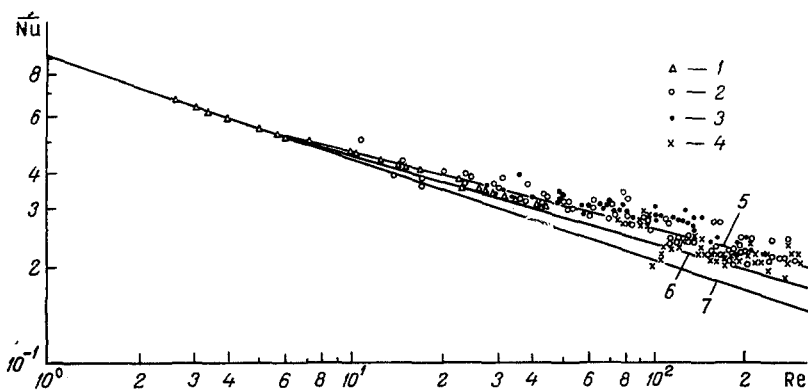


Fig. 1. Comparison of experimental data on heat transfer during condensation of a stationary vapor on a vertical surface with theoretical functions: 1) [4] (water); 2) [5] (Freons); 3) N. V. Zozulya (water); 4) S. S. Katateladze (water); 5) (2); 6) (1); 7) Nusselt theory.

case of condensation with a constant temperature head on a vertical surface, we obtain the following functions for the boundary of the development of the wave regime:

$$Re_w = 7(KPr)^{-3/8} Ka^{1/16}; \quad (3)$$

$$\frac{l}{l_\sigma} = 14(ReWe^{3/8})^{-0.67} = 14.56(KPr)^{1/2} Ka^{-1/12}; \quad (4)$$

$$\frac{l}{L} = 13.45 Re^{-4/3} (KPr)^{-1/2} Ka^{1/12} = 14 Re^{-2/3} We^{1/4}. \quad (5)$$

The correction to the intensification of heat exchange due to wave flow is determined through generalization of experimental results on heat transfer [4] on the basis of the theoretical relations (2) and (5) obtained:

$$\varepsilon_w = 1.0 Re^{0.053}. \quad (6)$$

An analysis of the proposed equations (2), (5), and (6) enabled us to distinguish the following characteristic regions of variation of the parameters of the condensation process.

For $KPr > 5$ the Reynolds number uniquely determines the heat transfer, since the value of $Ka^{1/12}$ varies insignificantly for a wide class of substances with $Pr \geq 1$. For $KPr < 5$ the laminar section occupies a considerable part of the length of the heat-exchange surface. For $Pr \approx 1$ and $Re = 40-50$, for example, the region of laminar flow comprises 40-50% of the length of the heat-exchange surface. This must be taken into account in the calculation of heat transfer, which in this case decreases by 10-15% in comparison with $KPr > 5$. With an increase in the Reynolds number, the influence of the complex KPr on the indeterminacy of the function $Nu(Re)$ decreases.

From the comparison of the results of calculations from (1) and (2) and the experimental data of various authors at $KPr > 5$ given in Fig. 1, it follows that the agreement of the proposed method with the experimental values is more precise. For $Re = 200-250$, for example, the average coefficient of heat transfer calculated from the proposed functions exceeds α_N by $\sim 30\%$ and exceeds the coefficient of heat transfer found from (1) by $\sim 15\%$. For $Re \leq 20$ the results of calculations from (1) and (2) practically coincide, while for $Re \leq 40$ the difference between them does not exceed 5%. When $Re > 40$, the length of the section of stable laminar flow is small compared with the length of the heat-exchange surface ($l/L < 0.05$), and so one can take $\bar{\alpha} = \varepsilon_w \alpha_N$ up to $Re = 250$, corresponding to the establishment of a self-similar regime of heat transfer.

The results obtained allow us to recommend the following function for calculating the average heat transfer during condensation of a stationary vapor on a vertical surface with $KPr > 5$:

$$Re < Re_w \quad \bar{\alpha} = \bar{\alpha}_N; \quad Re_w \leq Re \leq 40 \quad \bar{\alpha} = 0.95 Re^{0.04} \bar{\alpha}_N;$$

$$40 < Re < 250 \quad \bar{\alpha} = Re^{0.053} \bar{\alpha}_N.$$

In the case of $KPr < 5$ the heat transfer should be calculated from Eq. (2) with allowance for the corrections for the variability of the thermophysical properties of the condensate, convective transfer, and inertial forces in the condensate film [3].

NOTATION

L , Length of the heat-exchange surface; z , coordinate of the development of wave instability; x , current coordinate; $l_\sigma = \sqrt{\sigma/\rho_1 g}$, capillary constant; $l_\nu = (\nu_1^2/g)^{1/3}$, viscosity constant; σ , surface tension coefficient; ν , kinematic viscosity; ρ , density; $g = 9.81(1 - \rho_2/\rho_1)$ reduced acceleration of gravity; $K = \tau/C_p \Delta T$, Kutateladze number; Pr , Prandtl number, $Ka = (l_\sigma/l_\nu)^6$, Kapitza number; $We = (l_\sigma/L)^2$, Weber number; $Re = \bar{\alpha}_N \Delta T L / \nu_1 \rho_1 r = (4L/KPr l_\nu)^{3/4} / 3$, Reynolds number; $Nu = \bar{\alpha} l_\nu / \lambda_1$, averaged Nusselt number; $\bar{\alpha}$, average coefficient of heat transfer; r , latent heat of vaporization; C_p , specific heat; ΔT , temperature head. Indices: 1, 2, liquid and vapor, respectively; N , calculated from the Nusselt equation.

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HEAT-MASS TRANSPORT IN "CHEMICAL" LIQUID BOILING

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Using the reaction of zinc with hydrochloric acid as an example, an experimental and theoretical study is performed of transport phenomena. The coefficients obtained are compared to data on liquid boiling.

Chemical reactions with phase transitions related to liberation of a poorly soluble gas into a liquid occur quite widely in chemical technology. Their external appearance has much in common with liquid boiling on a heating surface, which has led to introduction of the term "chemical" boiling [1, 2]. Although there have been many studies of transport phenomena during metal solution in acids [3, 4], electrolysis [5], and catalytic decomposition of hydrogen peroxide [6] such questions require further clarification. Remaining specially unclear are results involving the heat and mass transport mechanism in "chemical" boiling, regions in which the reaction occurs, and hydrodynamic and thermal regimes.

Experimental Study of Transport Processes. The simplest chemical reaction which takes place with liberation of a gaseous phase is solution of metals in acids. Zinc and hydrochloric acid were chosen for study. The experiments to determine heat-mass transport principles for this reaction were performed under static conditions on zinc specimens in the form of 10 mm diameter spheres at an HCl concentration $C_{z1}^0 = 0.2$, liquid temperature $T_0 = 10-110^\circ\text{C}$, and pressure $P = 0.01-0.1$ MPa.

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